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Kinematic constraints on the rifting of Baja California

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Abstract

While the kinematic development of the Gulf of California and Baja California is poorly understood, the corresponding evolution of southern California and of the spreading in the mouth of the Gulf of California are relatively well known. The San Andreas fault has been increasingly active during the most recent ~17 m.y., culminating in its present slip rate of ~35 mm/yr 4-5 m.y. ago. Another ~20 mm/yr of right-lateral shear is inferred to exist on northwest trending faults near the southern California coast. In the mouth of the Gulf recent rifting history is also reasonably well constrained by magnetic anomaly patterns that record the Gulf motions during the most recent ~4 m.y. Spreading rate estimates here range from 50 to 65 mm/yr. Within southern California the present understanding of the recent kinematics is difficult to reconcile with spreading rates near 50 mm/yr, but is compatible with rates above this to about 65 mm/yr. Globally-constructed plate rate estimates predict rates that fall near the middle of the range of examined spreading rates, and can not be made compatible with the spreading rates near 65 mm/yr.

For any chosen spreading rate between 50 and 65 mm/yr, about 20 mm/yr of currently active right-lateral, trans-Peninsular slip is required, as well as a history of Gulf rifting that probably dates to the early San Andreas slip history. Trans-Peninsular slip presently is concentrated in (if not confined to) the northern Baja-southern California region, which feeds convergence in the Ventura Basin region. Prior to about one m.y. ago, however, trans-Peninsular activity is thought to have occurred principally on faults that crossed southern Baja California, and these faults probably account for ≥ ~100 km of net offset of southern Baja, and drove outer borderland shear and rotation of the western Transverse Ranges. Between roughly 4.5-17 m.y.B.P. the Gulf of California was developing through oblique rifting, but most of the relative plate motion was accommodated as shear outboard of the continent, a large fraction of which was occurring within the borderland.

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Introduction

It is a commonly held view that Gulf of California rifting began 4-5 m.y.B.P., and that Baja California has since moved with respect to North America at the Pacific-North America relative plate rate, accumulating ~300 km of displacement (Larsen, 1968; Moore and Curray, 1982). A major feature of this model is that the San Andreas fault is the transform fault which separates the Pacific Plate, upon which Baja rides, from the North American plate (as first suggested in Wilson, 1965). In a general sense there is little doubt that Baja has separated from North America in this manner. But significant deviations from this simple model are required by the presently available information, and these are important to understand if the historical development of the Gulf of California is to be determined, or more generally, if the nature of continental rifting processes are to be illuminated. The crux of the problem is that the magnetically recorded spreading history preserved in the mouth of the Gulf is interpreted to document significantly greater rates of motion than do offsets of geologic markers along the San Andreas fault. This leads one to seek a more complete and carefully constructed kinematic solution.

The slip histories of the major faults in southern California are well enough known to make a careful accounting, and it is found that the relative plate rate can be accounted for across southern California, but that ~20 mm/yr is outboard of the Peninsular Ranges (Weldon and Humphreys, 1986). This inboard-to-outboard transference of slip is accomplished primarily on right-lateral trans-Peninsular faults in northern Baja and southern California. When the geologic development of the southern California faults is considered, it becomes necessary (1) that such trans-Peninsular slip was occurring during much of the Gulf rifting, recently across the northern Baja-southern California region but earlier across southern Baja, and (2) that San Andreas-related transform-type slip has occurred in the Gulf region since ~17 m.y.B.P. This history is more protracted and complex than has been proposed by many workers (e.g., Moore and Curray, 1982).

Recent Deformation Related to Plate-Parallel Motion

The rate of motion parallel to the transform boundary of North America has been considered in a variety of ways and scales. Minster and Jordan (1978) have constructed a global kinematic plate model (i.e., "RM2") that, in particular, has the Pacific-North America plate velocity equal to about 56 mm/yr (along the western margin of North America), parallel to the transform faults in the Gulf of California. The strongest control on this velocity is not due to features attributable to the boundary between the Pacific and North America plates, but rather to those relating the relative motion of the other plates on the Earth's surface, and the need for self-consistency. This whole-Earth model has proven to be consistent with the available observations, and has become a standard reference with which more local kinematic models are compared. The formal 2σ uncertainty between the Pacific and North America plates is 3.3 mm/yr, though the model may tolerate up to, but not much more than ~5 mm/yr (Jordan, 1986). These values are very similar to those of the model ''NUVEL'' (Demets et al., 1985; Stein, 1986), a model that includes more recent data. While these are Quaternary models, others (Atwater and Molnar, 1973; Engebretson et al., 1985) have used similar kinematic principles to determine that the total Pacific-North America plate shear displacement has been about 1,800 km since the Pacific Plate first made contact with North America some ~30 m.y.B.P. Because this distance is much greater than the observed spreading in the mouth of the Gulf or the strike-slip offset in southern California, and because the inferred transform environment began much earlier than the related activity in these regions, the present San Andreas fault-related transform activity must be simply the recent expression of the long-standing but evolving tectonic setting. An important boundary condition supplied by this global modeling is the rather steady and lengthly application of approximately 60 mm/yr of shear to the portion of North America that lies adjacent to the Pacific Plate.

In the Gulf mouth, magnetic anomaly lineations have been interpreted by Larson et al. (1968) to indicate ~60 mm/yr of spreading over the preceding ~4 m.y., rates which are similar to those of Minster and Jordan (1978). More recent evaluation of these data, where information derived from the Rivera plate (mistakingly thought to be North America by Larsen et al., 1968) has been explicitly excluded, is interpreted to give either ~50 mm/yr or ~65 mm/yr (and not at an intermediate rate) (Ness, this volume). Ness prefers 65 mm/yr because this value yields a linear relationship between the age and the offset. The portion of rifting that produced oceanic crust totals almost 300 km. Prior to ~4 m.y. the history is much less certain because magnetic lineations were not formed. Withjack and Jamison (1986), in studies of other continental rifts, find that a pervasive tectonic disruption of the continental lithosphere occurs over an many millions of years. In the Gulf of California region, a proto-Gulf is substantiated by the deposition of marine sediments at various localities along the length of the Gulf in the time interval ~5-15 m.y.B.P. (Ingle, 1973; this volume). Also, Ness (this volume) finds the total separation of southern Baja from mainland Mexico to be at least 450 km. This is ~150 km more than inferred by Moore and Curray (1982) to have occurred as a result of rifting in the mouth of the Gulf, the excess amount being the result of including thinned and tectonically fragmented continental crust in the determination. Ness' determination assumes rifting to have been strictly parallel to the Pacific-North America plate direction of Minster and Jordan (1978). If rifting involved some normal component, the result would be to overestimate the total amount of separation that has occurred. However, any amount of separation beyond that represented by oceanic crust with preserved magnetic lineations must must have occurred prior to the formation of the magnetic anomalies (i.e. prior to ~4 m.y.B.P.), and is therefore thought to have originated during the earlier continental disruption phase of the rifting.

It is commonly believed that slip on the San Andreas fault (and faults of direct kinematic relation) has allowed for the rifting of Baja, but while the modern episode of slip on the San Andreas fault has been continuously active since the times of the early rift history of the proto-Gulf (i.e., since roughly 15 m.y.B.P), no more than 330 km of total slip can be accounted for on the San Andreas fault (Dickinson et al., 1972, and many others). Also, the slip history on the San Andreas fault (or the San Andreas fault and San Jacinto fault south of Transverse Ranges) has been worked out well enough to state that the recent slip rates here are disparate with the spreading rates in the mouth of the Gulf; there is and has been about 35 mm/yr (Weldon, 1986; Sieh and Jahns, 1984) of such slip for the last 4-5 m.y.

Significant strain rates not kinematically associated with the San Andreas fault is attributed to the Ventura Basin region with the recognition of high rates of convergence (23 mm/yr: Yeats, 1983; 17 mm/yr: Rockwell, 1984; Rockwell et al., 1984), and possibly additional significant, ongoing convergence in the Santa Barbara Channel to the south. Because the region of strong convergence is confined to the western Transverse Ranges, this region is thought to be a left step in a right-lateral strike-slip fault system that closely follows the coast (Weldon and Humphreys, 1986). When this ~20 mm/yr is combined with the slip rate of the San Andreas fault, rates roughly equivalent to the total plate rate are obtained, and so the deformation observed in the western Transverse Ranges is thought to be an integral part of the plate margin strain field at this latitude.

The available information, if accurate, places limits on where and at what rates the slip redistribution may be occurring. Starting with the fault nearest to the San Andreas fault, the San Jacinto fault leaves the San Andreas fault-related transform system in the Salton Trough, but rejoins the San Andreas fault in the Transverse Ranges (and is therefore part of the San Andreas-related ~35 mm/yr). The Elsinore-Laguna Salada fault system, which splays from the San Andreas-related transform system south of the international border and cuts northwest across the Peninsular Range in southern California, appears to transfer 5-6 mm/yr of slip (Pinault and Rockwell, 1984; Rockwell, this volume) from the Gulf of California to the Los Angeles Basin. Thus this slip is not related to the San Andreas fault, but instead probably contributes to the convergence in the Ventura Basin. Further southwest, the remaining loci of potential Ventura Basin-feeding faults are probably confined, at present, to the faults near and just off shore: the Newport-Inglewood-Rose Canyon faults, the Coronado Bank-Palos Verdes faults, and the San Diego Trough. Given the northwest trend of the major faults in the borderland, faults west of the San Diego Trough probably cannot contribute to convergence in the Ventura Basin, and in fact the San Diego Trough itself may lie too far to the west (see Figure 2). This inference does not disallow the occurrence of slip on these faults, but such slip is expected to be independent of convergence in the Ventura Basin, and its contribution to the total relative plate velocity should therefore be in addition to that found on the San Andreas fault and in the Ventura Basin. According to Legg (this volume) the Rose Canyon, Coronado Bank, and San Diego Trough faults are fed by the Agua Blanca fault, and are not fed by faults south of this. Therefore, any Baja-crossing or Baja-circumventing deformation south of the Agua Blanca fault is thought not to contribute to the combined ~55 mm/yr observed on the San Andreas fault and in the Ventura Basin. (The San Miguel-Vallecitos fault, just to the northeast of the Agua Blanca fault, apparently contributes its slip to the Rose Canyon fault, but no other faults have been identified that contribute to these near-shore faults).

Using this fault geometry, a strain rate budget in the western Transverse Ranges region can be estimated. Convergence in the western Transverse Ranges at the longitude of the Ventura Basin is thought to be at least 15 mm/yr (this is 2 mm/yr less than the estimate of Rockwell et al., 1984), and is probably closer to 20 mm/yr (obtained by averaging the estimates of Rockwell et al., 1984, and Yeats, 1983). About 3 mm/yr may be due to the convergence across the central Transverse Ranges (Weldon and Humphreys, 1986), and 5-6 mm/yr can be attributed to the Elsinore fault (Pinault and Rockwell, 1984; Rockwell, this volume). The implication is that at least 6 mm/yr of slip, and probably about twice this amount, is due to the Agua Blanca and San Miguel faults. Interestingly, preliminary work on the main trace of the Agua Blanca fault indicates rates of only about 4 mm/yr (Rockwell, this volume).

Implications for the Gulf

To illustrate the implications of reconciling the information from both the Gulf mouth and southern California, we select three spreading rates for the mouth of the Gulf to examine: 50, 56, and 65 mm/yr.

50 mm/yr spreading rate- This rate is examined because it is one of the possible spreading rates of the Tamayo spreading center as interpreted by Ness (this volume). If 50 mm/yr is the relative plate rate, there is a need to explain the discrepancy between this value and the 56 mm/yr obtained by Minster and Jordan (1978). One possibility is that the uncertainty reported by Minster and Jordan has been underestimated, but they argue that the internal consistency of the world-wide information is strong (an argument supported by Stein, 1986) and that there is greater uncertainty associated with the kinematics of the local Gulf of California region. The problem can be solved by having an additional 6 mm/yr provided by strain not represented by the magnetic anomalies of the Tamyo spreading center. Two possibilities exist: (1) Slip completely outboard of the continent may be occurring (e.g., near the west coast of Baja, Yeats and Haq, 1981). Considering the likelihood that significant rates of slip were occurring here prior to the initiation of the modern San Andreas fault, this *ad hoc* construction may not be too far fetched. Although there is no significant seismicity recognized on any structure of appropriate location south of the international border, there is reason to believe right-lateral shear is occurring in the outer borderland off of southern California (this possibility is discussed briefly in the final paragraph of this section on recent San Andreas fault-parallel slip). (2) The Jalisco block may be translating to the northwest. This block is rifting from mainland Mexico, but because this rifting has been active for the last 4.6 m.y. (Allan, 1986; this volume) the rate of rifting is probably < 1 mm/yr. Also potentially important may be slip on the trans-Mexican volcanic belt, though the graben separating the Jalisco block from Mexico north of the trans-Mexican volcanic belt (see Figure 1) displays principally rift, and not shear, deformation (Allan, 1986; this volume).

In California, a solution compatible with 50 mm/yr of spreading can be hypothesized that has the San Andreas fault slip rate estimate ~35 mm/yr (Weldon, 1986; Sieh and Jahns, 1984) and the minimum of ~15 mm/yr across the western Transverse Ranges. This solution matches the assumed spreading rate in the mouth of the Gulf, while avoiding the need for additional shear strain across Baja south of the Agua Blanca fault (which is in accordance with both the reported geologic features of Baja (Sawlan, this volume; Ortlieb, this volume) and the observations offshore that faults outboard of Agua Blanca fault do not feed into the

San Diego Trough or faults to the east (Legg, this volume) and thus probably do not contribute to the convergence seen in the Ventura Basin. It also allows all of the assumed Pacific-North America spreading to enter the Gulf, which is reasonable considering the distance into the Gulf mouth that the Tamayo spreading center lies.

This scenario is the most compatible of the three with respect to the land-based geodetic work. Strain rates of only about 35 mm/yr have been observed across the San Andreas fault and the region to the west (assuming San Andreas fault-parallel, simple shear strain), even when observing to points as far west as the Farallon Islands (located at the latitude of San Francisco) (Prescott and Yu, 1986). An additional ~5 mm/yr of right-lateral shear has been reported east of the San Andreas fault in the Mojave desert region (Sauber and Thatcher, 1984, and Sauber et al., 1986) based on studies of land-based geodetic records. A small fraction of the total strain may have been missed in these geodetic surveys because it occurs in the far field, but it would be difficult to argue that the available data support net rates greater than about 50 mm/yr east of the Farallon Islands.

The major problem with this option is the requirement that the sum of the convergence rate in the Ventura Basin and the shear across the Mojave region totals only ~ 15 mm/yr, and that all other potential regions of strain accumulation are not presently active (assuming the San Andreas rate of 35 mm/yr is valid). If strain is occurring across the Mojave, the strain rate in the Ventura Basin must be well below the lowest estimate for that region.

56 mm/yr spreading rate- This spreading rate is chosen to be the same as the rate of Minster and Jordan (1978). It is also comfortably compatible with the kinematic situation in southern California (Weldon and Humphreys, 1986). A problem with this option is that, while it is between the extremal estimates for spreading rate in the mouth of the Gulf, 56 mm/yr is not equal to any of these rate estimates. It is closest to the estimate of Larsen (1968) and Moore and Curray (1982) of 60 mm/yr. If this rate (or any greater rate) is assumed, another problem that has to be dealt with is that of matching conditions both in the Gulf mouth and in southern California without violating the kinematic constraints as they are presently understood. There are several possible ways these two regions can be kinematically related, but each implies certain unsatisfying situations.

Accounting for 56 mm/yr of strain in southern California is most naturally accomplished with ~20 mm/yr of convergence in the Ventura Basin region. Following the arguments made above in the paragraph on the western Transverse Ranges strain rate budget, this implies either ~10 mm/yr of slip rate on the Agua Blanca and San Miguel faults or some transference of slip from faults south or west of the Agua Blanca-San Diego Trough system onto this system. Alternatively, we may postulate the extreme lower limit of convergence rate in the Ventura Basin and then include ~5 mm/yr of right-lateral shear east of the San Andreas fault, such as has been suggested by Sauber and Thatcher (1984) and Sauber et al. (1986).

65 mm/yr spreading rate- This rate is chosen for the purpose of comparing to the ~65 mm/yr spreading rate preferred by Ness (this volume) for the mouth of the Gulf. This rate is greater than that allowed by the global plate rate model of 56 mm/yr (Minster and Jordan, 1978), though as mentioned above, this modeled rate has only weak *direct* control between the North America and Pacific Plates. If the 65 mm/yr rate is real, either the mismatch with the Minster and Jordan rate would have to be discounted (on the grounds that it is not well constrained) or significant rates (i.e., ~10 mm/yr) of left-lateral shear are required across the trans-Mexican volcanic belt (Ness, this volume), and thus no magnetic lineations in the Gulf mouth lie on stable North America Plate. If this later option is correct, the kinematics north of the trans-Mexican belt are the same as in the 56 mm/yr option above.

A slip rate in southern California of 65 mm/yr is hard to reconcile with the land-based geodetic work (Prescott et al., 1979; Savage, 1983; Prescott and Yu, 1986), but they are supported by some of the initial space-based geodetic results which suggest that Vandenberg (near Point Conception, California) is moving towards Alaska at ~60 mm/yr (Clark, 1986).

Requiring 65 mm/yr of slip across southern California will necessitate having slip rates on the San Andreas fault and in the Ventura Basin near their maximal limits, and having significant right-lateral shear occurring either to the east of the San Andreas fault, or having significant rates of shear occurring west of the San Diego Trough. Considering the above-mentioned problems with supplying > 20 mm/yr of convergence to the Ventura Basin region, the most likely solution is to have ~20 mm/yr in the Ventura Basin, ~5 mm/yr of shear occurring across the Mojave (as suggested by Sauber and Thatcher, 1984, and Sauber et al., 1986), and also have roughly ~5 mm/yr of shear in the outer borderland. The physiography and seismicity of the outer borderland region argue for its modern activity, as does the recognition of young convergence in the Santa Barbara Channel and the large amounts of clock-wise rotation of the Channel Islands (~30° in ~ 5 m.y., Kamerling and Luyendyk, 1985, and Luyendyk, 1986). The existence of these rates of shear in the outer borderland, when taken in conjunction with spreading in the Gulf mouth at 65 mm/yr, seems to require present trans-Peninsular shear south of the Agua Blanca fault.

Previous San Andreas Fault Parallel Slip

The observations cited to this point pertain to only the most recent activity. If the geologic development of the region is considered, the constraints become more informative. The Elsinore and modern Newport-Inglewood faults are both thought to be only recently active faults (< ~1 m.y.B.P.) of small offset, implying a less active Ventura Basin region before ~1 m.y.B.P. This is in agreement with observations in the Ventura Basin (Yeats, 1983; Rockwell, 1984). (In the recent past convergence may have been more active in the Santa Barbara Channel to the south of the Ventura Basin, but by the above arguments, should have been at less than present Ventura Basin rates). The recency of convergent activity in the Ventura Basin, when taken with the evidence that the San Andreas fault slip rate has been constant for the last 4-5 m.y., implies (1) the non-San Andreas southern California-latitude deformation was concentrated further offshore than it is at present, and therefore (2) either lower spreading rates in the mouth of the Gulf, or trans-Peninsular or Baja-circumventing slip were occurring. The age vs. offset relation of the magnetic lineations under the 65 mm/yr spreading rate option produces roughly constant spreading rates over the last ~4 m.y. (Ness, this volume), which in turn implies a total of ~30 mm/yr of Baja crossing or circumventing strain over this duration. The 50 mm/yr choice of spreading rate produces a non-linear trend in the age vs. offset plot, with a small rate of spreading in the interval ~2-3 m.y.B.P., but then greater rates 3-4.5 m.y.B.P., necessitating ≥20 mm/yr of Baja crossing or circumventing strain during the older interval.

Between ~5 and ~17 m.y.B.P. the San Andreas fault was accumulating up to ~180 km of its ~330 net km of slip (Dickinson et al., 1972; Weldon and Meisling, 1986). Because the San Andreas fault leads into the Salton Trough on its southern end, it seems unavoidable that large amounts of right-lateral shear continued into the northern Gulf of California region during this interval of time. It is therefore probable that the 330 km recorded offset on the San Andreas fault and the ≥300 km of oblique opening of the northern Gulf of California (Moore and Curray, 1982; Ness this volume) are and have been kinematically coincident. If this conclusion is true, Gulf rifting has been occurring since the initiation of modern, southern California San Andreas-related slip (i.e., ~17 m.y.B.P., Powell, 1986; Meisling and Weldon, 1986). It is possible that this early San Andreas-related slip in the northern proto-Gulf crossed the Peninsular Ranges and never affected the southern proto-Gulf. But the southern Gulf has witnessed even greater amounts of net offset, and at ~15 m.y.B.P. the Pacific-North American-Cocos triple junction has been calculated to be at its the present site (Engebretson, 1985) or about 100 km to the north of this (Dickinson and Snyder, 1979). It therefore seems probable that the San Andreas-related slip involved at least most of the Gulf.

Discussion

Three Gulf of California spreading rates have been examined (50, 56, and 65 mm/yr). Considering the limits of our present geologic knowledge, any of these are possible. Spreading rates beyond the limits of this range, however, begin to violate what is thought to be known about the geology, and within these limits one does not have independent freedom in choosing spreading rate, plate rate, and Peninsular Ranges kinematics.

The differences in the three trial spreading rates are accommodated primarily with different strain rates in the borderland. Regardless of spreading rate choice, accommodating the outer borderland presents a bit of a problem. On the one hand, the seismicity and physiography of the borderland, and the large clock-wise rotations of the Channel Islands and western Transverse Ranges suggests that the region south of the Channel Islands is under considerable shear (≥~5 mm/yr?). But the existence of outer borderland shear leads to the problem of its kinematic source; either the actual relative plate rate must be greater than predicted by Minster and Jordan (1978) (making available the extra strain rate that is needed to allow outer borderland shear), or the 50 mm/yr Gulf of California is correct (leaving ~5 mm/yr to distribute across the outer borderland).

If we now combine the Neogene history of the region with the information pertaining to the ''present'' kinematics, we can address the geological development of the Gulf region. It seems well established that the San Andreas fault was active well before magnetic lineations were being formed in the mouth of the Gulf. And while it is probable that early San Andreas slip had been directly linked to the separation in the mouth of the Gulf, this does not alleviate the need for much of the rift-related slip to have gotten outboard of Baja, either on Baja-crossing faults (such as those suggested by Rusnak et al., 1964) or on thrust faults just south of Baja's southern tip. This requirement arises because the northern trans-Peninsular faults which presently feed Ventura Basin convergence, and account for much (if not all) of the present slip rate discrepancy between the Gulf mouth spreading rate and the San Andreas slip rate, were not significantly active prior to ~1 m.y.B.P.

In southern California, the San Andreas fault has been slipping at a rate of ~ 35 mm/yr since ~4.5 m.y.B.P. (Meisling and Weldon, 1986). The ~33 km of observed offset on northwest trending right-lateral faults in the Mojave Desert (which occurred since 20 m.y.B.P.) (Dokka, 1983) suggests that this region was also accommodating some of the deformation related to the opening of the Gulf. Geodetic strain measurements in the Mojave region indicate presently occurring deformation in the same region, and if this strain is arising from slip on these recently active faults, it is occurring at ~5 mm/yr (Sauber and Thacher, 1984 and Sauber et al., 1986). It seems most reasonable to assume (in lieu of more complete information) that the Mojave faults were slipping at a constant rate over the same interval of time in which the nearby San Andreas fault was slipping at a constant rate, i.e., for the last ~ 4.5 m.y. However, prior to ~1 m.y.B.P. both the Agua Blanca (Allen et al., 1960) and Elsinore (Kennedy, 1977) faults are thought to have been relatively inactive. No other faults are known in southern California or northern Baja that could have participated significantly in this activity at this time. Thus the total slip rate on southern California faults that could have accommodated the opening of the Gulf amounts to ~40 mm/yr.

In the mouth of the Gulf, the rate of opening was 50-65 mm/yr for at least the last 4-4.5 m.y.B.P. (4.5 m.y. at 50 mm/yr, 4 m.y. at 65 mm/yr; Ness, this volume). If the 50 mm/yr spreading rate option is assumed, the net difference in offset that occurred between 1 and 4.5 m.y.B.P. would have been 35 km, while under the 65 mm/yr spreading rate option the net difference in offset that occurred between 1 and 4 m.y.B.P. would have been 75 km. (Under the low spreading rate option the resulting magnetic anomaly age vs. offset relation implies that the spreading rate was at markedly lower between approximately 2 and 3 m.y.B.P. (Ness, this volume), and thus the accumulation of the 35 km of offset would have occurred primarily between ~3 and ~4.5 m.y.B.P.) Because the magnetic anomalies preserved during spreading are found well into the mouth of the Gulf, it seems probable that rift-related strain entered the Gulf, and did not get around Baja's southern tip. If this is so, the difference in strain rate must have been taken up as slip on faults which cross Baja. Furthermore, because faults in the northern Gulf are thought to have had a similar slip history as that of the San Andreas fault (see last paragraph before discussion), the faults on which the earlier trans-Peninsular slip occurred are probably south of central Baja.

The difference between estimated amount of rifting at the mouth of the Gulf and estimated amount of rifting in the northern Gulf can be used to estimate the total amount of southern trans-Baja shear since the inception of rifting. Assuming all rifting to have occurred parallel to the relative plate motion, Ness (this volume) estimates ≥450 km for the amount of opening in the mouth of the Gulf (for the Tamyo spreading center). This contrasts with the estimate of Ness (this volume) for the northern Gulf that is 150 km lower. Any rifting in the Colima Graben or shear across the trans-Mexican volcanic belt would change the amount of rifting at both sites by the same amount, and would not alter the difference between the two.

And if any subduction that may have occurred at the southern tip of Baja during rifting is ignored, its only possible affect on the determination of relative amounts of rifting would be to underestimate the total amount of opening in the mouth of the Gulf, and thus to underestimate the difference between the southern and the northern Gulf opening (and hence to underestimate the amount of southern trans-Baja slip that would have occurred). Thus the Gulf geometry suggests that ~150 km of southern trans-Baja slip has occurred since the rifting of Baja began. At least part (and possibly half) of the southern trans-Baja slip occurred ~1-4 M.Y.B.P., but as the northern trans-Peninsular faults became increasingly active over the last ~1 m.y., their southern counterparts became correspondingly inactive.

If the large amounts of rather steadily accumulating rotation seen in the western Transverse Ranges (~30° during the preceding ~5 m.y., ~90° during the ~15 m.y.B.P., Luyendyk, 1986) is real, this has probably been accomplished by having considerable amounts of shear distributed across the borderland (in a model similar to the Transverse Range rotation model of Luyendyk et al. (1980), but which includes only the western Transverse Ranges). Southern Baja crossing faults, such as those hypothesized above, would be capable of supplying this shear rate to the borderland, and if the spreading rate in the Gulf mouth has been roughly at the relative plate rate over the last ~4 m.y., there is no other obvious feature capable of supplying this shear rate because the plate motion has been entirely accommodated by opening in the mouth of the Gulf. Prior to the time when the opening in the Gulf mouth was at or near the plate rate, the difference between the plate rate and the opening rate of the mouth must have been occurring as slip outboard of the continent, and could have quite naturally supplied the shear necessary to rotate the western Transverse Ranges. The suggestion that the borderland is comprised of a horizontally repeated Franciscan-Great Valley terrain along or in the vicinity of the present San Clemente fault (Crouch, 1979; Teng, this volume) implicates this feature as a major actor, and suggests that this fault lessened in rate in direct correspondence to the increase in activity within the Gulf and on the San Andreas fault. If the history discussed above is valid, it would imply a cessation or reduction in rotation rate of the western Transverse Ranges as the borderland shear budget became increasingly dominated by its eastern fraction during the most recent ~1 m.y.

It has been noted that the Murray Fracture Zone is alinged with the western Transverse Ranges, which are themselves alinged with the central and eastern Transverse Ranges (e.g., Hadley and Kanamori, 1977). Considering the differing tectonic histories experienced by each section of this linear array of structures, this is quite remarkable. A brief, speculative history of the region is constructed below that accounts for this structure, which builds on the work of many others.

The fault slip history discussed above may be used to predict the locations of the Murray Fracture Zone and the various tectonic elements in the southern California-northern Baja region with respect to North America. At ~8 m.y.B.P. (Figure 3a) the Murray Fracture Zone was about 450 km south of its present location (assuming a constant ~56 mm/yr relative plate rate), and southern California west of the San Andreas fault was ~200 km south of its present location (assuming a San Andreas slip history of Meisling and Weldon, 1986, which is similar to the compilation of Atwater and Molnar, 1973). Restoring offset on the San Andreas fault for the duration 0-4.5 m.y.B.P. moves the central Transverse Ranges to just south of the eastern Transverse Ranges. Prior to this time much of the San Andreas-related slip occurred south of both incipient mountain ranges, on the now nearly inactive San Gabriel fault (Ehlig, 1981; Crowell, 1982). Placing the Murray Fracture Zone 450 km south of its present location with respect to North America puts it 250 km south of its present location with respect to the portion of southern California west of the San Andreas system. This is approximately where the western tip of the western Transverse Ranges would have been if the ~50° of clock-wise rotation that is thought to have occurred here since this time (Kamerling and Lyendyke, 1985, and Luyendyk, 1986) are restored while the eastern tip of the western Transverse Ranges (i.e., in the eastern Ventura Basin) remained fixed with respect to southern California west of the San Andreas fault. This spatial coincidence suggests that the western Transverse Ranges were somehow "caught" and then "carried" by the Murray Fracture Zone on its journey north (Engebretson, 1985, discusses a potential mechanism for this process). Similarly, the central Transverse Ranges may have been "caught" by the Murray Fracture Zone/western Transverse Ranges at about 4.5 m.y.B.P. as this pair of features became roughly alinged with the (proto-) central and eastern Transverse Ranges. It is at this time slip on the San Gabriel fault subsided (Ensley and Verosub, 1982), and the San Andreas fault attained its present, maximum slip rate of ~35 mm/yr (Weldon, 1986; Weldon and Meisling, 1986), possibly in response to the fault realingment that removed the convergence-producing "knot" required by the San Gabriel fault geometry with the simple-shear geometry presented by the San Andreas fault (Weldon and Humphreys, 1986). Figure 3b shows the inferred situation at about 3 m.y.B.P.

Finally, two brief topics are discussed that have not found a convenient place, but are nevertheless worthy of discussion.

The location and nature of initial rifting at the southern tip of Baja was probably related to the position of the Pacific-North American-Cocos triple junction and the geometry of the slab-free "window" as a function of time (the kinematics of which have been discussed by Dickinson and Snyder, 1979). The location of the triple junction through time, as determined by global plate reconstructions, is somewhat uncertain though. Dickinson and Snyder (1979) have it migrating south past the southern tip of Baja at a rate of about 25 mm/yr about 5 m.y.B.P. Engebretson (1985), on the other hand, has it located roughly in the same position for the last ~15 m.y. Given the uncertainty in its globally inferred location, it seems likely that the geologic information of the southern Baja region may be itself the best constraint on the migration of the triple junction. If rifting were to begin at about ~17 m.y.B.P., it is possible, within our present understanding of the triple junction geometry at this time, that this began in the present mouth of the Gulf. It is also possible that initial rifting was located about 150 km further to the north.

There has been some discussion of a "soft margin" to the continent (e.g., Atwater, 1970) allowing for "distributed shear". By making use of this mechanism, otherwise unaccounted-for shear can be included in kinematic models, and in this way be made compatible with other models or with limited data sets. Such distributed shear may in fact be occurring, but the ability to model southern California and Baja kinematics without it (or, alternatively, the small amount of unaccounted-for strain that is present in the kinematic models) argues that only a small fraction of the total plate motion is being taken up in the volume between the major faults. Of course, the ~40 km spacing of major strike-slip faults roughly parallel to the continental margin may be considered "distributed" in this incremental fashion, and thus could be thought of as constituting a "soft" margin.

Acknowledgments

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Figure Captions

Fig. 1. Simplified tectonic map of the Gulf of California region. Map is Mercator projection about the North America Plate (NAPlate) Pacific Plate (PPlate) relative pole of Minster and Jordan (1978). Numbers are rates in mm/yr, with the Minster and Jordan rate of 56 mm/yr shown with the large arrow (North America assumed fixed). In the mouth of the Gulf the relative plate rate is mostly or entirely accommodated with spreading observed on the Tamyo spreading center (tsc), while at the latitude of southern California the San Andreas fault (saf) carries only about 35 mm/yr of slip. Most of the remaining the slip crosses the northern peninsula on strike slip faults (i.e., the Agua Blanca fault, abf, and the Elsinore fault, ef) which feed convergence in the Ventura Basin (VB). Some slip is occurring on the San Clemente fault (sclf), but the source and rate of this strain is unknown. The total deformation zone probably lies inboard of the Patton Escarpment, shown with the dotted line.

Fig. 2. Simplified fault map of the northern Baja-southern California region. This map shows the complexity of the main tectonic elements of the region, which have been greatly simplified in Figure 1. Symbols given in Figure 1 are not repeated here. Notice that convergence in the Ventura Basin is fed by faults crossing the northern peninsula, the Agua Blanca, San Miguel (smf), and Elsinore faults, and not by faults outboard of these, such as the San Clemente fault, or inboard of these, such as the San Jacinto fault (sjf) (which leaves the San Andreas fault in the Salton Trough (ST) but rejoins the San Andreas to the north). This statement is based on the work of Legg (this volume) that the Agua Blanca fault does not join with the San Clemente fault, but does join with the Rose Canyon-Newport-Inglewood fault system (rc), the Coronado Bank-Palos Verdes fault (pvf), and the San Diego Trough (sdt). The borderland faults and the Elsinore fault trend northwest, but do not cross the western Transverse Range structures, represented here by the Ventura Basin and the Malibu Coast-Santa Cruz (sczf) fault system. Also shown for reference is the Garlock fault (gf).

Fig. 3. Schematic tectonic development of the Gulf of California region. Shown on these figures are the major faults thought to be active at the indicated time, where the arrows represent approximate rates of slip. The Transverse Ranges (western, w; central, c; eastern, e) trend east-west across the present tectonic, geologic, and physiographic grain of the region. The specification of the Transverse Range sections at times prior to the present is not meant to imply that mountain ranges stood in the indicated sites at these earlier times, but simply to indicate the earlier location of the regions. Also shown is the approximate latitude of the Murray Fracture Zone (mfz) with respect to North America.

(a) At 8 m.y.B.P. the San Andreas fault may have been slipping at about 15 mm/yr. This probably approximately matched the rate of opening in the mouth of the Gulf, though probably small additional rates of spreading (5-10 (?) mm/yr) were occurring that was accommodated on southern trans-Peninsula faults. Most of the relative plate rate must have been occurring outboard of the continent.

(b) At 3 m.y.B.P. the relative plate rate entered the Gulf, but 10-15 mm/yr of shear probably crossed Baja south of the northern Gulf. The remaining ~40 mm/yr of shear was taken up primarily on the San Andreas fault and faults in the northern Gulf of direct kinematic relation.

(c) At present the western Transverse Ranges are alinged east-west with the Murray fracture zone. Relative plate motion (~60 mm/yr) enters the mouth of the Gulf. This strain is accommodated further north primarily on the San Andreas fault (~35 mm/yr) and on a more nearshore system of faults (~20 mm/yr of shear on the southern California-Baja California trans-Peninsular faults, of convergence on the Ventura Basin, and of shear on faults trending northwest from the westernmost Transverse Ranges).

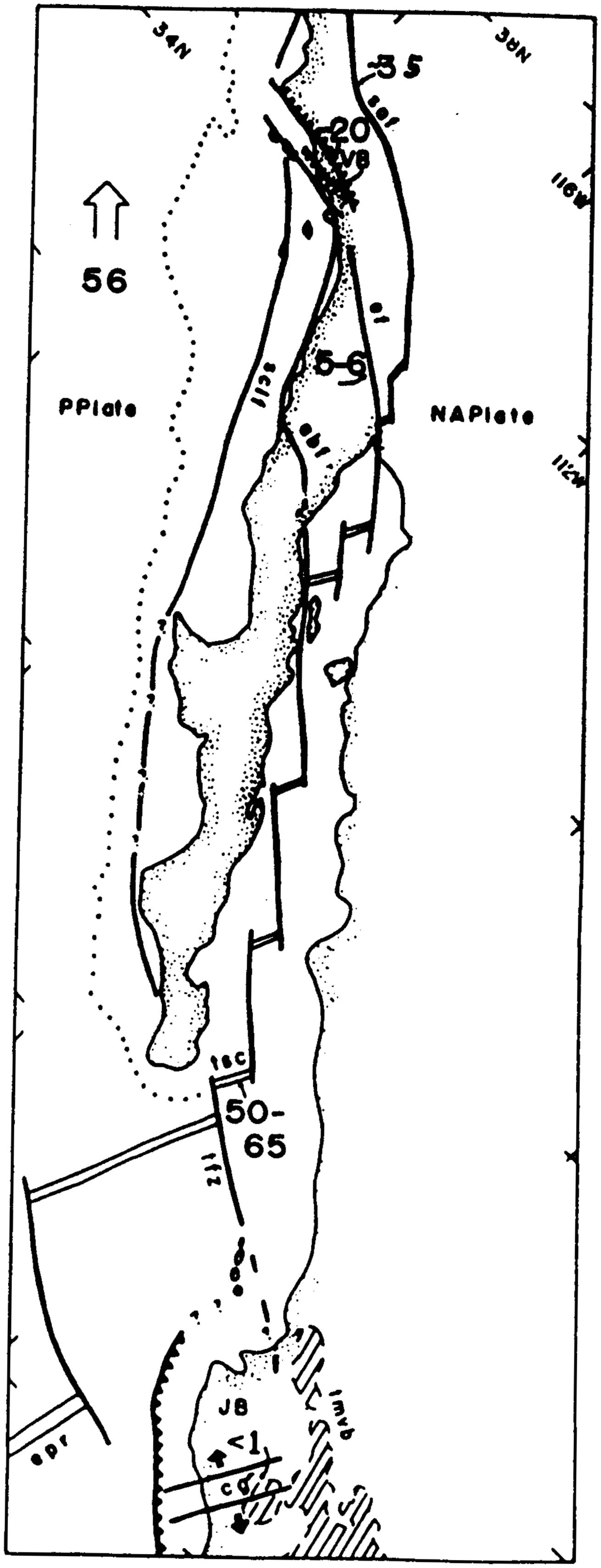

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Figure 1

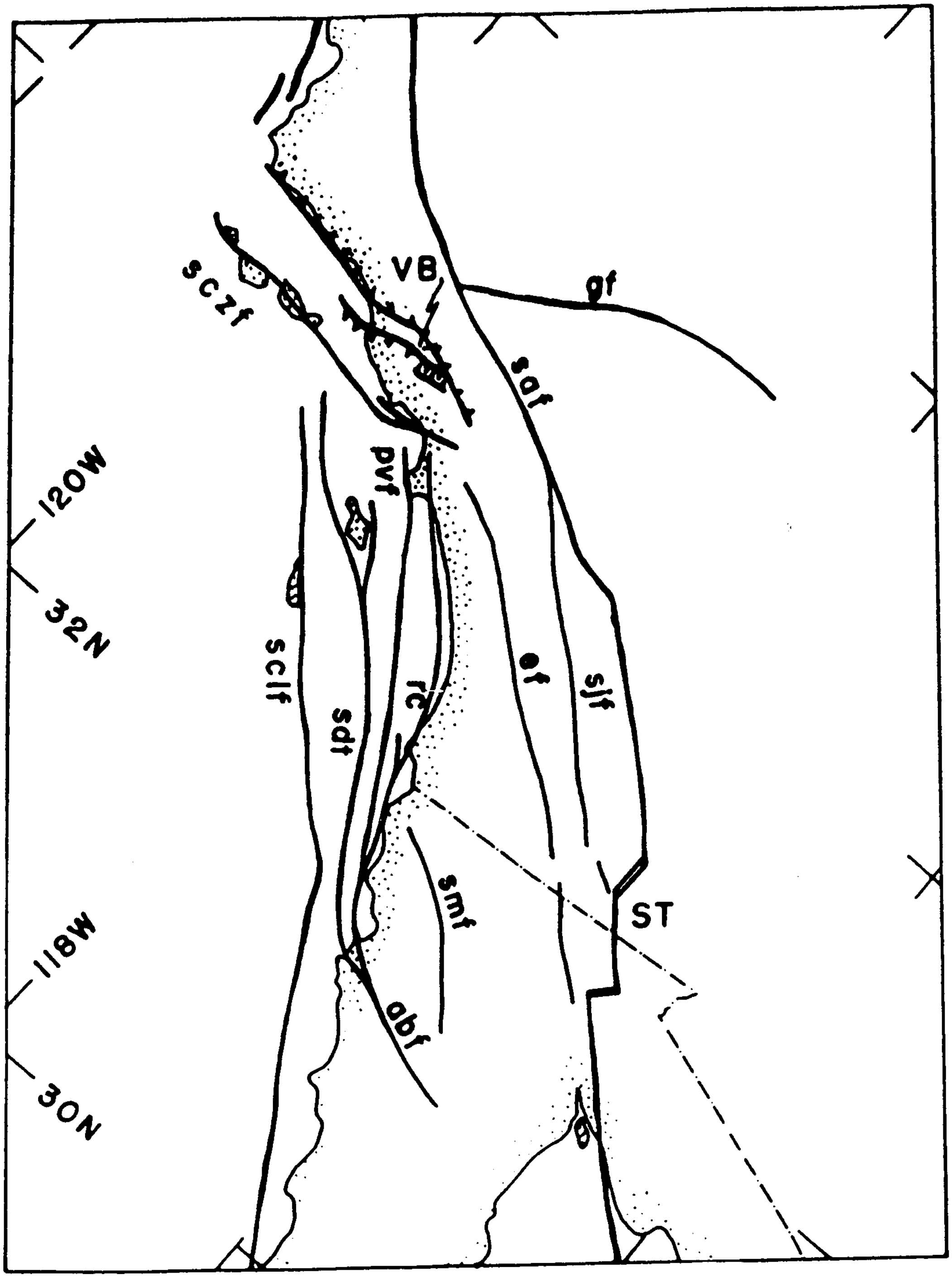
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Figure 2

Figure 3